Geology as a proxy for V_{s30} -based seismic site characterization, a case study of northern Pakistan

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Abstract

Earthquakes, with their unpredictable and devastating nature, have resulted in large damages worldwide. Seismic site characterization maps (SSCMs) are frequently and effectively used to demarcate the locations that are prone to amplified seismic response. The time-averaged shear wave velocity of top 30 m of earth surface (V_{s30}) is effectively used as a parameter to evaluate seismic amplification. Northern Pakistan is one of the most seismically active region in the world with 2005 Kashmir earthquake as the most devastating natural disaster. However, for most of the country, the seismic site characterization maps are not available. Geological units and topographic slope are used as proxies for V_{s30} -based SSCMs around the world and in northern Pakistan. However, the studies in northern Pakistan are lacking field-based validation of the estimated V_{s30} and hence the proxy-based SSCMs might be unrealistic. The aim of this study is to correlate instrument-based V_{s30} measurements with geological units and remote sensing-derived topographic slope to develop a more realistic SSCM for the study area, located in the seismically active northern Pakistan. Geology of the study area has significant impact on the estimated V_{s30} and hence is used as a proxy for SSCM. The developed SSCM shall assist in developing earthquake mitigation strategies in the region.

Keywords V_{s30} · Geology · Shear wave velocity · Seismic site characterization · Northern Pakistan

Introduction

Earthquakes are proved to be the most devastating natural disaster with a high mortality rate and widespread destructions. Earthquake-induced ground shaking plays a key role in intensity and magnitude of infrastructure damages, and in triggering secondary hazards such as landslide, flood, tsunami, fire, and liquefaction. Intensity and duration of an earthquake-induced ground shaking depends on magnitude of the earthquake, depth of hypocenter, fault nature, medium traversed by seismic waves, and physical and geotechnical characteristics of the site (Geli et al. 1988; Kramer 1996;

Hartzell et al. 2001; Bakır et al. 2002; Ozel and Sasatani 2004; Narayan 2010; Szeliga et al. 2010; Panzera et al. 2014; Panzera et al. 2015). Spatial variation of ground shaking, at a local scale, is influenced by the physical and geotechnical characteristics of the site (Kramer 1996). Evaluating the site impacts on ground shaking is of crucial importance to develop seismic site characterization maps that can be further used for mitigating the impacts of earthquakes.

Seismic site characterization maps (SSCM) are frequently used for earthquake mitigation, preparedness, response, and recovery. Developing SSCM at a regional scale, however, requires extensive investment in geological and geotechnical data acquisition and interpretation, and therefore, for many of the seismically active areas, SSCM are rarely available (Shafique et al. 2012). One of the parameters, commonly used as an indicator of seismic site conditions, and therefore often used in SSCM, is the time-averaged shear wave velocity of the top 30 m earth surface (V_{s30}) (Borcherdt 1994; Hartzell et al. 2001; Wills and Clahan 2006; Wald and Allen 2007; Yong et al. 2008; Castellaro and Mulargia 2009; Shafique et al. 2012). The V_{s30} -based SSCMs are used by the USGS at global scale (Wald et al. 2006) in developing ground shaking maps using ShakeMap, and seismic loss estimates in near real-time using

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Prompt Assessment of Global Earthquakes for Response (PAGER) (Earle et al. 2008) and by the National Earthquake Hazards Reduction Program (NEHRP) to define generalized seismic site categories (Table 1) (Wills et al. 2000).

Measuring V_{s30} at a regional scale, however, is practically and economically not feasible. This has led to attempts to use geology, geomorphology, and topography as a proxy for geotechnical properties and regolith thickness providing thereby means for estimating V_{s30} at a regional scale (Wills and Silva 1998; Wills et al. 2000; Matsuoka et al. 2005; Shafiee and Azadi 2007; Thompson et al. 2007; Wald and Allen 2007; Yong et al. 2008; Shafique et al. 2012). The control of underlying geological units on estimated V_{s30} was observed by Wills et al. (2000), Wills and Clahan (2006), and Shafiee and Azadi (2007). Wald and Allen (2007) observed the significant impact of topographic slope on V_{s30} measurements and subsequently used remote sensing-derived topographic slope as a proxy for estimating V_{s30} with a global coverage. In line with this, Shafique et al. (2012) and Yong et al. (2008) used remote sensing-derived topographic slope to map geomorphic units such as basins, piedmont, and mountains, as a proxy for sediment thickness and geology and divided these into V_{s30} classes. However, these proxies-based estimations of V_{s30} at a regional scale are prone to uncertainties, given the unavailability of in situ V_{s30} measurements. The aim of this research is to collect in situ estimates of V_{s30} using geophysical instrumentation in the earthquake-affected area of northern Pakistan. Subsequently, evaluate the impact of local geology and topographic slope on estimated V_{s30} and develop a realistic SSCM for the study area.

Study area

Pakistan is located in one of the most seismically active regions on earth. The Indian tectonic plate is subducting northward beneath the Eurasian plate at a rate of 31 mm/year (Bettinelli et al. 2006) and has resulted in the development of world's highest, i.e., Karakoram, Himalaya, and Hindu Kush Mountain ranges in the northern and northwestern parts of the country. The active tectonics in the region have resulted in accumulation of the tremendous subsurface stresses that are released in frequent earthquakes with devastating impacts. Earthquakes in northern Pakistan are often associated with

the east–west trending regional thrust faults, i.e., Main Karakoram Thrust (MKT), Main Mantle Thrust (MMT), and Main Boundary Thrust (MBT) (Fig. 1a).

Northern and northeastern portions of Pakistan have experienced strong earthquakes in recent past. The Muzaffarabad Fault in the Hazard Kashmir Syntaxis was ruptured on 8th of October 2005, resulting in the Kashmir earthquake (Fig. 1b). The Kashmir earthquake is declared as the most devastating catastrophe in the history of Pakistan, killing 86,000 people, leaving millions of people homeless, and producing significant economic losses (ADB and WB 2005). The cities of the Balakot and Garhi Habibullah were the site of severe devastations in the 2005 Kashmir earthquake and hence are selected for this study (Fig. 1b). Geology of the area comprises of lithologies that are predominantly of sedimentary and meta-sedimentary in origin including sandstone, shale, slates, schist, and limestone (Fig. 2b and Table 3) (Hussain et al. 2004; Latif et al. 2008). The active tectonics and host to many faults (MBT, Muzaffarabad, Murree, Panjal) and folds (Hazara Kashmir Syntaxis) lead to jointing and fracturing of these lithologies and therefore play a crucial role in the seismic site characterization.

Methodology

Instrument-based V_{s30}

The V_{s30} in the study area was estimated using geophysical instrument of Tromino Engy Plus that allows measuring vibrations, tremors, H/V curves, and V_{s30} (Castellaro and Mulargia 2009; Castellaro and Mulargia 2009b; Roser and Gosar 2010). Experimental determination of horizontal to vertical (H/V) curves was performed by a three-directional (longitudinal, transverse, and vertical) digital tromograph (Micromed Tromino). H/V is derived from the horizontal-vertical spectral ratio (HVSr) technique that is frequently used to estimate site-specific amplification of earthquake-induced ground shaking. The method was originally proposed by Nogoshi and Igarashi (1971) and widely spread after Nakamura (1989) and consists of estimating the ratio between the Fourier amplitude spectra of the H/V components of ambient noise vibrations signals recorded at a site. There is a

Table 1 Definition of NEHRP site classes in terms of V_{s30} (BSSC 2001)

Site class	Range of V_{s30} m/s	Geologic description
A	$1500 < V_{s30}$	Very hard rocks
B	$760 < V_{s30} \leq 1500$	Rocks
C	$360 < V_{s30} \leq 760$	Hard or very hard soils, gravels, soft rocks
D	$180 < V_{s30} \leq 360$	Hard soils (sands, clays, and gravels)
E	$V_{s30} \leq 180$	Soft clays of thickness about H in site profiles

Fig. 1 Location map of study area. **a** The regional E-W trending thrust faults. **b** Study area is overlaid on the ASTER DEM. The Muzaffarabad fault is the causative fault of the 2005 Kashmir earthquake

consensus among the researchers that the H/V ratio allows to estimate the principal resonance frequency of the sediment cover overlying infinite bedrock. For the simplest case of a single-layer, one-dimensional stratigraphy, the fundamental resonant frequency is given by

$$f_o = Vs/4H \quad (1)$$

where V_s is the average shear-wave velocity in the sediment layer and H is the sediment thickness. The microtremor HVSr method does not directly provide the shear-wave velocity profile, but this can be derived by modeling the H/V ratio curve provided that a constraint (on h or V_s) is available from independent surveys. Thus, by assuming a stratified, one-dimensional soil model for the wave field and for the medium, a theoretical HVSr curve can be fitted to the experimental one to infer a subsoil model (Castellaro and Mulargia 2009).

In the study area, the instrument was placed on a natural bare ground for 20 min with a sampling frequency of 128 Hz at 132 sites. The H/V data was recorded mostly along the exposed outcrops and geotechnical well log. The recorded data was processed in the Grilla code (Castellaro and Mulargia 2009a; Castellaro and Mulargia 2009b). This code

generates synthetic H/V curves based on the simulation of the surface-wave (Rayleigh and Love) field in plane-parallel multi-layered systems, according to the theory described in Aki (1965) and Ben-Menahem 1981

The code can process models with (1) any number of layers, (2) any frequency interval, and (3) any number of modes (fundamental and higher). In this study, maxima inside the frequency range of [0.5, 20 Hz] of engineering interest were considered. The recorded Grilla traces were processed in agreement with the international consensus criteria (Table 2) of SESAME (EU 2004). According to which, we have verified the conditions for a reliable curve, i.e., (a) sufficient number of windows ($f_o > 10/Lw$); (b) significant number of cycles ($n_c = Lw n_w f_o$), and (c) acceptably low level of scattering between all windows. Subsequently, we have checked the clarity of the H/V peaks (i.e., fulfillment of amplitude and stability criteria) to reduce the noise of wind blowing, near building effects, bad soil-sensor coupling, etc. Eventual peaks induced by low-frequency (0.1–1.0 Hz) disturbances were removed by varying the smoothing parameters, to better resolve broad or multiple peaks. These processing parameters, analysis, and interpretation of the collected instrument-based trace are given in Fig. 2.

Fig. 2 **a** ASTER DEM-derived topographic slope of the study area with estimated V_{s30} samples. **b** Geological map after Hussain et al. (2004) and Latif et al. (2008) with estimated V_{s30} samples

V_{s30} estimation from SPT-N and H/V data

The Grilla traces were interpreted for clear and reliable peaks. A constraint was fitted as a thickness of first layer from the collected 39 geotechnical well log information. Average shear wave velocity for the 30-m depth (V_{s30}) was calculated as the time for a shear wave to travel from a depth of 30 m to the ground surface (Borcherdt 1994). As shown in Eq. (2), the time-averaged V_{s30} is calculated as 30 m divided by the sum of the travel times for shear waves to travel through each layer. The travel time for each layer is calculated as the layer thickness (H) divided by V_s . Finally, the average shear wave velocity values in the upper 30 m (V_{s30}) were calculated in accordance with the following expression:

$$V_{s30} = \frac{30}{\sum_{i=1,n} \frac{h_i}{v_i}} \quad (2)$$

where h_i and V_i denote the thickness (in meters) and the shear-wave velocity of the i th layer, in a total of N , existing in the top 30 m.

Standard penetrating test (SPT) data from the collected well logs of 30-m depth, by the National Engineering Services Pakistan (NESPAK), were selected. SPT-N data

was converted to shear wave velocity using empirical models by Seed and Idriss (1981), Imai and Tonouchi (1982), Iyisan (1996), Lee and Tsai (2008), and Tsiambaos and Sabatakakis (2011). H/V-based shear wave velocity (V_{s30}) was compared with shear wave velocity (V_{s30}) calculated using selected empirical models (Dikmen 2009; Akin et al. 2011).

Topographic slope and geology as proxy for SSCM

To evaluate the impact of topographic slope and geological formations on V_{s30} , the estimated V_{s30} is correlated with the topographic slope and geology of the study area. Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)-derived digital elevation model (DEM) with 30 m spatial resolution is acquired to compute topographic slope for the study area using ArcGIS software (Fig. 3a). The geological map of the study area (Fig. 3b) mapped by Hussain et al. (2004) and Latif et al. (2008) is acquired (Table 3).

The V_{s30} data is collected, purposively, on the classified topographic slope and geological formations. Subsequently, their impact on estimated V_{s30} is being evaluated. The number of V_{s30} estimations collected on each slope class and geological formation is according to their spatial coverage, in the

Table 2 SESAME criteria for clear and reliable H/V curves

Criteria for a reliable H/V curve [All 3 conditions should be fulfilled]	
1	$f_0 > 10 / L_w$
2	$n_c(f_0) > 200$
3	$\sigma_A(f) < 2$ for $0.5f_0 < f < 2f_0$ if $f_0 > 0.5$ Hz $\sigma_A(f) < 3$ for $0.5f_0 < f < 2f_0$ if $f_0 < 0.5$ Hz
Criteria for a clear H/V peak [At least 5 out of 6 conditions should be fulfilled]	
1	Exists f^- in $[f_0/4, f_0] \mid A_{H/V}(f^-) < A_0 / 2$
2	Exists f^+ in $[f_0, 4f_0] \mid A_{H/V}(f^+) < A_0 / 2$
3	$A_0 > 2$
4	$f_{\text{peak}}[A_{H/V}(f) \pm \sigma_A(f)] = f_0 \pm 5\%$
5	$\sigma_f < \sigma(f_0)$
6	$\sigma_A(f_0) < \sigma(f_0)$
Where	
L_w	Window length
n_w	Number of windows used in the analysis
$n_c = L_w n_w f_0$	Number of significant cycles
f	Current frequency
f_0	H/V peak frequency
σ_f	Standard deviation of H/V peak frequency
$\sigma(f_0)$	Threshold value for the stability condition $\sigma_f < \sigma(f_0)$
A_0	H/V peak amplitude at frequency f_0
$A_{H/V}(f)$	H/V curve amplitude at frequency f
f^-	Frequency between $f_0/4$ and f_0 for which $A_{H/V}(f^-) < A_0/2$
f^+	Frequency between f_0 and $4f_0$ for which $A_{H/V}(f^+) < A_0/2$
$\sigma_A(f)$	Standard deviation of $A_{H/V}(f)$, $\sigma_A(f)$ is the factor by which the mean $A_{H/V}(f)$ curve should be multiplied or divided
$\sigma_{\log H/V}(f)$	Standard deviation of $\log A_{H/V}(f)$ curve
$\sigma(f_0)$	Threshold value for the stability condition $\sigma_A(f) < \sigma(f_0)$

study area, to have an equal representation of the topography and geology. The seismic site characterization map (SSCM) is developed for the study area using the field-based V_{s30} estimations and geological map of the area. The significance of the developed SSCM is evaluated by comparing it with the 2005 Kashmir earthquake-induced building damage data developed by Shafique et al. (2012).

Results and discussions

Calibration of the estimated V_{s30}

The comparison of SPT-N-derived V_{s30} with the H/V-based estimations of V_{s30} shows that the trend between averages V_{s30} is similar (Fig. 4 and Table 4). Since we are interested in the average near-surface velocities as an indicator of seismic site condition, it gives us confidence that the instrument-based estimated V_{s30} is representative of the actual near-surface composition.

In Table 4, Daharian has low average V_{s30} of 183 m/s estimated based on H/V which is same as the SPT-N-derived V_{s30} value and classified as soil site D. Very loose quaternary stream deposits are present in this area. It is very interesting to note that, at Garlat 8, average V_{s30} estimated based on H/V results 173 m/s which indicate soil site class E, in contrary to SPT-N-derived V_{s30} value (235 m/s) resemble soil site class D. This difference might be occurred in the processing of Tromino traces, due to the smoothing effect of the sharpness of the peak of the fundamental curve. By reducing 0.1 point in the amplitude of the peak, shear wave velocity reduces about 10–15 m/s. As stated earlier, smoothening was done to remove the noise effect.

Shoal Najaf has maximum average V_{s30} of 385 m/s estimated based on H/V which is quite similar to the SPT-N-derived V_{s30} and categorized in soil site class C containing very dense soil and soft rock of Murree Formation, Patala Formation, and Margala Hill Limestone. Most of the study area categorized in soil site class D with H/V-based average V_{s30} values ranges from 206 to 353 m/s. This belongs to the presence of stiff soils of Quaternary alluvium, Quaternary Terrain, and Quaternary stream deposits.

Fig. 3 Processing parameters, analysis, and interpretation of the collected Grilla trace

Correlation between V_{s30} and topography

The relationship between the estimated V_{s30} with the ASTER DEM-derived topographic slope shows very weak correlation of $R^2 = 0.04$ (Fig. 5). Similarly very weak correlation of $R^2 = 0.08$ is observed by comparing the ASTER DEM-derived terrain elevation and the measured V_{s30} (Fig. 6).

Hence, contrary to the findings by Wald and Allen (2007), topographic slope cannot be used as a proxy for V_{s30} -based SSCM in the study area, partly because of the very diverse topography, geology (Fig. 3), and anthropogenic interventions in the local landscape. The results are in line with the findings of Burjáněk et al. (2014), where they observed no relation between seismic amplification and topographic features;

Table 3 Geological formations with corresponding lithology in the study area as described by Hussain et al. (2004) and Latif et al. (2008)

Geological formations	Lithology	Age
Quaternary deposits	Sand, clay, silt and gravels and loose clay, silt and gravel	Quaternary to recent
Murree Formation	Dominantly shale and siltstone with subordinate sandstone and conglomerate	Miocene
Patala Formation and Margala Hill Limestone	Interbedded shale, marl, and nodular limestone	Paleocene-Eocene
Mansehra Orthogenesis	Porphyritic granite-granodiorite with large feldspar phenocrysts. Where sheared, turned into augen gneisses. Intruded by tourmaline granite, meta gabbro, amphibolite and pegmatite	Early Cambrian
Muzaffarabad Formation	Cherty, massive to thick bedded, hard, rubly dolomite and limestone	Early Cambrian
Tanawal Formation	Predominantly quartzite. Where sheared, turned into quartzose schist	Late Precambrian
Hazara Formation/Manki Slate	Pyllite, slate, sandstone, and shale	Late Precambrian
Salkhala Formation	Quartz-mica schist, graphitic schist, calcareous schist, subordinate to rare recrystallized limestone	Early Precambrian

Fig. 4 Comparison of V_{s30} derived from SPT-N using different empirical models with instrumentally collected V_{s30}

however, the subsurface properties have significant influence on the seismic amplification. The weak topographic control on estimated V_{s30} can be attributed to the presence of different geological formations along the same slope, within short distances that is in consensus with the observations of Pedersen

et al. (1994). Furthermore, Shafique et al. (2011) has shown that distinct and significant variations in regolith thickness exist in the area, which is known to have a strong impact on V_{s30} . Moreover, almost flat surfaces on mountain top, with higher elevation but no, or very little, regolith, are also

Table 4 Comparison of V_{s30} derived from conversion of SPT data from several drilled sites using different empirical equations (rows 1–5) with that derived using the Tromino (row 6) at the same two sites

Site	Longitude (E)	Latitude (N)	Vs30 (m/s) from SPT-N derived Relations					Average of a,b,c,d,e (m/s)	V_{s30} , H/V (m/s)	SC
			a*	b*	c*	d*	e*			
Talhatta-1	73°21.51	34°26.05	304	381	339	347	315	337	339	D
Garlat-10	73°21.09	34°31.87	228	243	213	258	256	240	237	D
Jabri-1	73°22.15	34°29.09	313	397	354	358	322	349	318	D
Guldheri	73°22.34	34°24.10	304	380	338	347	315	337	307	D
Hassari	73°21.10	34°31.55	276	329	272	284	283	289	276	D
Hassa	73°21.70	34°26.30	247	284	250	287	275	269	243	D
Garlat-1	73°21.09	34°31.19	281	338	300	320	297	307	281	D
Garlat-6	73°21.10	34°31.55	254	293	259	289	275	274	251	D
Shoal	73°21.13	34°34.39	325	421	375	372	331	365	353	D
Garlat-8	73°21.14	34°32.62	224	239	210	253	250	235	173	E
Jalora	73°21.18	34°32.62	235	259	228	266	260	249	229	D
Narra	73°20.75	34°27.43	221	236	208	250	248	233	214	D
Khait Sarash	73°21.41	34° 31.77	227	239	209	256	255	237	219	D
Shigai	73°20.42	34° 33.61	230	246	216	260	256	242	223	D
Jabri-3	73°21.86	34°29.13	246	275	242	278	269	262	241	D
Banda Dalola	73°21.12	34°26.75	294	365	325	336	307	326	298	D
Garlat-7	73°21.54	34°33.34	253	290	256	288	275	272	250	D
Balakot-1	73°20.94	34°33.80	215	221	193	242	244	223	206	D
Daharian	73°21.41	34°31.77	194	188	163	218	227	198	183	D
Talhatta-2	73°21.70	34°26.30	271	319	282	308	289	294	270	D
Balakot-2	73°20.86	34°33.66	267	313	277	304	286	290	266	D
Shoal Najaf	73°21.86	34°29.13	381	395	368	377	371	378	385	C

Fig. 5 Correlation of estimated V_{s30} with the ASTER DEM-derived topographic slope

contributing to the weak correlation of measured V_{s30} with topographic slope. Therefore, often, it is difficult to distinguish between a purely topographic effect and the influence of underlying lithological variations, also in agreement with the Panzera and Lombardo (2013). Anne et al. (2012) proposed that seismic site characterization using terrain slope, and V_{s30} correlations suggested by Wald and Allen (2007) can be effectively used for regional or national first-order studies in seismically active areas, but shall not be used for local or site-specific investigations. For site-specific studies,

more detailed field-based investigations shall result in more realistic results.

Correlation between measured V_{s30} and geology

Contrary to topography, significant control of the underlying geology on the estimated V_{s30} is observed in the study area, as was previously observed by Wills and Silva (1998), Wills et al. (2000), Wills and Clahan (2006), and Shafiee and Azadi (2007). Within each geological formation, variation in V_{s30} is

Fig. 6 Correlation of estimated V_{s30} with elevation

Fig. 7 The spread of estimated V_{s30} in different geological formations

observed (Fig. 7). The influence of compositional variation, regolith thickness, land cover, weathering intensity, and geo-technical properties on V_{s30} leads to the variation in estimated V_{s30} (Fig. 7). Due to the internal variation in the quaternary deposits, from very soft materials to the presence of river-deposited gravels in the sedimentary deposits and variation in the regolith thickness, the measured V_{s30} for this unit varies between 164 m/s and a maximum of 430 m/s, respectively. This is in agreement with the remote sensing-based classification by Shafique et al. (2012) and Yong et al. (2008), who mapped basins over the same region of quaternary deposits and assigned V_{s30} values of < 300 m/s. The highest variation in the measured V_{s30} is observed in the Patala Formation and Margala Hill Limestone (Fig. 7). This is mainly due to a broad variety of lithologies present in most units, varying from strong to weak. The level of weathering is another factor that can lead to varying V_{s30} values. There is, however, a clear division between more stiff and weaker units. The highest

V_{s30} values in the area are estimated from hard rocks, including porphyritic granite-granodiorite, augen-flaser gneisses, tourmaline granite, and pegmatite in the Mansehra orthogenesis unit (Fig. 7). Figure 7 shows positive skewness for the V_{s30} measurements in Mansehra Orthogenesis, Tanawal Formation, and Hazara Formation/Manki Slate showing that majority of the measurements has higher V_{s30} . The observed significant influence of the geological formation on the estimated V_{s30} is in line with the observation of Wills et al. (2015), Yong (2016), and Anne et al. (2012).

The mean of estimated V_{s30} of different geological formations is given in Table 5. The mean V_{s30} of 297 m/s is observed (Table 5) on quaternary deposits, unconsolidated material with fluvial deposits, which was also observed by Wills et al. (2000) and Wills and Clahan (2006). Based on the observed significant control of geological formations on estimated V_{s30} , the geology map (Fig. 3b) of the study area is used as a proxy for a V_{s30} -based SSCM. The geological map of the

Table 5 Geological formations and estimated V_{s30} in the study area. All mean V_{s30} are classified in NEHRP classes (Table 1)

Geology	Min-Max V_{s30}	Mean V_{s30}	NEHRP Class
Quaternary deposits	160–430 m/s	297	D
Murree Formation	320–580 m/s	446	C
Patala Formation and Margala Hill limestone	320–770 m/s	549	C
Mansehra orthogenesis	640–940	837	B
Muzaffarabad Formation	470–650 m/s	559	C
Tanawal Formation	480–850 m/s	713	C
Hazara Formation/Manki slate	430–830 m/s	696	C
Salkhala Formation	510–860 m/s	703	C

Fig. 8 **a** V_{s30} -based seismic site characterization map of the area. **b** Seismic site characterization map according to the NEHRP classes, both maps based on the measurements and classification as given in

Table 5. **c** Remote sensing and field information-based structural damages induced by the Kashmir earthquake after Shafique et al. (2012) and Shafique et al. (2011)

study area (Fig. 3b) is reclassified on the basis of mean estimated V_{s30} , to derive a seismic site characterization map (Fig. 8a). Subsequently, Fig. 7a is reclassified to the NEHRP classes (Table 5; Fig. 8b).

Comparison of estimated V_{s30} with damage data

To evaluate the significance of the SSCM, and to evaluate if it can be used for the prediction of seismic induced damages, the derived V_{s30} -based SSCM is compared with remote sensing-based Kashmir earthquake damage data after Shafique et al. (2012) and Shafique et al. (2011) (Fig. 8c). The comparison of the SSCM (Fig. 8a) with the 2005 Kashmir earthquake damage data (Fig. 8c) shows that for the severely damaged areas, the estimated V_{s30} is, on average, 307 m/s. For the moderately damaged areas, the observed V_{s30} is on average 620 m/s. This confirms that despite the lack of relation with topography, the impact of estimated V_{s30} on ground shaking amplification and consequently building damages is present and showing a clear relation. Comparison of the developed SSCM with the earthquake damage data strengthens the hypothesis that low V_{s30}

leads to amplification of ground shaking and subsequently intense structural damages, also observed by Hartzell et al. (2001).

Conclusions

To evaluate proxies for seismic amplification, we have collected instrument-based V_{s30} estimates in the seismically active region of northern Pakistan. The estimated V_{s30} was compared with SPT-derived V_s and comparable results have been found. V_{s30} obtained from the instrument-based measurements is therefore further used as a representative indicator for subsurface conditions. Relations are sought with the topography and geology. A weak correlation of the estimated V_{s30} with the topography is observed in the study area, contrary to Wald and Allen (2007). The estimated V_{s30} is, however, significantly controlled by the underlying geology. Hence, the geology of the study area is used as a proxy for a V_{s30} -based SSCM. There is a good correlation between the SSCM and earthquake-related damage in the region. The

lower V_{s30} region in the developed SSCM has experienced severe structural damages during the 2005 Kashmir earthquake. The derived V_{s30} -based seismic site characterization map can be used to formulate strategies for earthquake disaster management in the study area.

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